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(6) MEASUREMENTS REQUIRED FOR PREDICTION OF HIGH ENERGY LASER TRANSMISSION.

By

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Accurate predictive models are required for design, testing, and field use of high energy laser systems. The success of these models for transmission predictions including linear and nonlinear effects is made possible only by the availability of a good atmospheric parameter data base which must include turbulence, crosswind, gaseous absorption, and aerosol extinction. A review is given herein of the status of this data base for White Sands Missile Range, the effects recent measurements made by the Atmospheric Sciences Laboratory have on high energy laser transmission predictions, and facility capabilities available with

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plans to resolve remaining problem areas. No attempt is made to select the best laser source, but several effects are discussed which may have direct bearing on such a choice.

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PREFACE

The authors wish to express their deep appreciation to Glenn B. Hoidale for many helpful comments for organizing this paper and for his timely review. Also to be thanked are Ronald G. Pinnick for his data input to the aerosol portion of the text and Colburn L. Norton for his data input to the turbulence and crosswind portions of the text.

CONTENTS

INTRODUCTION

As design advances in HEL systems continue, the interest by the Army, Navy, and Air Force in the HEL as a tactical air defense weapon is steadily increasing. The basic problem in fielding an HEL system is how to build a device which can transmit enough of the power from an HEL source through the atmosphere to destroy or disable an enemy target. Accurately predicting atmospheric transmission under a variety of conditions is of paramount importance to the design, testing, and eventual use of an HEL weapon system.

An HEL weapon and its enemy target may be located at any elevation in the earth's atmosphere. As a result, the optical paths of interest are quite varied as are the parameters which describe them. Among the elements used to describe a normal atmospheric path are meteorology (turbulence, crosswind, temperature, and pressure), aerosols (size distributions, number density, chemical composition, scattering coefficients, and absorption coefficients), and gases (molecular species, concentrations, and absorption coefficients). Hence, modeling predictions for transmission of HEL systems under just normal atmospheric conditions are quite complex. Add to the above a battlefield environment with its exotic mixture of exhausts and particulate matter perhaps even a countermeasure smoke; plus naturally occurring low visibility conditions from rain, snow, fog, clouds, or dust storms; and a few nonlinear propagation effects such as thermal blooming, kinetic cooling, wet aerosol absorption, and air breakdown. The result is that present transmission models cannot be used to accurately predict transmission under many atmospheric conditions.

There are too many essential pieces of data missing from present models to use them for laser source selection, not to mention design changes such as wavelength selection and maximum usable total power. Though the present picture is not rosy, obtaining meaningful predictive models is not an impossible task. Recent research advances have resulted in measurements of vital new data which have improved transmission model predictive capabilities and furnished the equipment capabilities to perform several more needed experiments. Because of the many problems involved, the timely fielding of an HEL weapon system will require a realistic and well coordinated development program with continual input from both user and researcher.

Presented in this report are several recent transmission measurements/ measurement capabilities which have been performed/developed by the Atmospheric Sciences Laboratory (ASL) at White Sands Missile Range (WSMR), NM, and have direct impact on HEL weapon system development and testing. The general approach will be to give linear effects such as absorption and scattering measurements since nonlinear effects such as thermal blooming are expressed in terms of them.

LASERS AND PROBLEM AREAS

There are four serious contenders for potential HEL sources. These lasers radiate in or near the 3-5 and 8-12μm atmospheric transmission window regions where the molecular absorption is low and aerosol extinction is much less than at visible wavelengths. The lasers are hydrogen fluoride (HF, 2.6-3.1μm), deuterium fluoride (DF, 3.5-4.1μm), carbon monoxide (CO, 4.7-5.2μm), and carbon dioxide (CO_2, 9.2-9.8 and 10.1-11.0μm). At present, the CO_2 laser is the most advanced designwise, the HF is the most efficient yet has the poorest transmission due to large water vapor absorption, the DF appears to have the best overall transmission characteristics, and the CO has only a few emission lines with relatively high transmission. A complicating factor for modeling predictions of the transmission of these lasers for the chemical laser versions is that they have multiline output modes.

The continental aerosol model [1] and molecular absorption line parameter tabulation [2] are useful in defining some general transmission problem areas. No attempt will be made here to duplicate the details of the transmission problems covered in an excellent review article by Gebhardt [3]. Some of the areas of interest discussed are noteworthy. First, degradation due to atmospheric turbulence has been reduced under limited range conditions by the use of active or adaptive optics [4]. Measurements of the refractive index structure constant (C_N^2), which is used to calculate beam spread due to turbulence, are very important for field testing of an HEL system [5]. Second, the crosswind speed and slewing rate of an HEL are important in determining thermal blooming and optimum pulse repetition rate for pulsed sources for effects like the creation of stagnation zones. Crosswind sensors developed for the ASL have application in the use of HEL systems [6]. Third, the effect of absorption on thermal blooming is usually greater for gases than aerosols. More specifically water vapor absorption with its so-called continuum absorption is present throughout the infrared, carbon dioxide and ozone at CO_2 wavelengths are especially important for high altitude use where the absorption lines narrow with reduced pressure broadening, and battlefield related absorption is not even well-defined at this time. Last, aerosol extinction (absorption plus scattering) can become the dominant factor in transmission under low visibility conditions. The absorptive properties of atmospheric dust vary geographically because of variations in composition. Also the relative effectiveness of countermeasure smokes are not well known.

MEASUREMENT CAPABILITIES

To adequately address field testing of an HEL system, a very unique facility is required. Several atmospheric parameters of interest have never been adequately measured and require state-of-the-art advances to obtain model predictions accurate enough to determine how well an HEL system performs and what can be done to improve it. The ASL has made great strides toward resolving many of the data gaps and developing the measurement

capabilities needed to support meaningful field testing of an HEL system. Success along these lines has been made possible largely by a well-oriented and timely laboratory measurement and development program. Table 1 summarizes the measurement devices and their capabilities which will be discussed in this paper.

The ASL has laboratory facility capabilities for both gaseous absorption and aerosol characterization. Techniques to measure the absorption coefficients (imaginary refractive indices) of particulate matter were initiated by using spectrophotometers in the visible and near infrared [7]. Measurement capabilities have been extended to the 3-5 and 8-12μm regions using pellet spectrophones [8]. Calibrations of aerosol spectrometers such as the Knollenberg counter for particles of different complex refractive indices have been performed [9]. The result is a more reliable aerosol size distribution and number density measurement capability. In addition uniquely designed resonant differential spectrophones are being readied for field use as in situ measurement devices for measurement and separation of the atmospheric absorption from gases and aerosols [10]. Measurements of gaseous absorption, including the important water vapor continuum in the 3-5μm atmospheric window, have been made possible only through experimental breakthroughs in the use and design of temperature controlled spectrophone and longpath absorption cell systems. Resonant subchamber as well as pulsed source spectrophones were developed at the ASL [11]. Also a path differencing technique was initiated for use with longpath absorption cells to greatly reduce long-term system drift and decrease data acquisition time [12]. Finally, diode laser capabilities have been added which can be used to support the development of a field Fourier transform transmissometer into a device which can obtain integrated path profiles of the species and concentrations of the absorbers present.

Field instrumentation for HEL testing support is also being addressed. In addition to the in situ spectrophone system, calibrated aerosol spectrometer, and Fourier transform transmissometer already mentioned above, other equipment and supportive data bases are being obtained. Crosswind sensors are very much needed for HEL field testing and have been perfected at the ASL [13]. A path profiling crosswind system was developed because of the special importance to beam quality of the effects of the atmosphere near the source and target. Point samplers are being used to obtain altitude and time dependence of a variety of atmospheric parameters which include temperature, pressure, gaseous species and concentrations, aerosol size distributions and absorption and scattering coefficients, crosswind speed, and atmospheric turbulence which is measured with high-speed temperature probes developed by ASL.* The ASL is also contributing to the geographical aerosol data base through measurement of the vertical profiles of aerosol size distributions in low visibility fog and haze atmospheres [14].

**Refinements in the design of turbulence sensors [6] have been made by D. L. Walters, ASL, WSMR, NM.*

TABLE 1

MEASUREMENT CAPABILITIES

Device	Quantity: General — Aerosol (A), Crosswind (C), Gases (G), Meteorology (M), Turbulence (T); Specific — absorption (abs), composition (com), extinction (ext), size distribution and number density (siz)	Measurement Used For: Laboratory (L)/ Field (F) and Point (P)/ Integrated Path (I)	Comments
Point Samplers (wide variety)	A(siz, com), C, G(com), M, T	F,P	General-purpose devices commercially available
Turbulence Sensor	T	F,P	High-speed temperature probe which indirectly measures C_N^2
Crosswind Sensor	C	F,P/ I	Time displays can be produced along entire path of interest
Aerosol Spectrometer	A(siz)	L/ F, P	Calibration is being performed for aerosols of different composition
Fourier Transform Transmissometer	A(com, ext), G(com, ext)	L/F, I	High resolution devices must be used
Path Profiling System	A(ext), C, G(ext)	F, P	Nonintegrated path profiles obtained
Spectrophotometer	A(abs)	L/ F, P	Field samples are analyzed in the laboratory (visible and infrared)
Pellet Spectrophone	A(abs)	L/ F, P	Field samples are analyzed in the laboratory (3-5 and 8-12μm windows)
Resonant Differential and Pulsed Source Spectrophones	A(abs), G(abs)	L/ F, P	Relative measurements made in situ with CW and pulsed sources
Longpath Absorption Cell	G(abs, ext)	L, I	Absolute extinction and absorption (gaseous scattering insignificant in the infrared)
			Calibration of spectrophones and Fourier Transform Transmissometer
Diode Laser	A(ext), G(ext)	L/ F, P/ I	Used with longpath cells or spectrophones to obtain frequency dependence of extinction

TURBULENCE

The most important feature of atmospheric turbulence to HEL transmission is the beam spreading which it causes. Typically expressed in terms of C_N^2, the refractive index structure constant, atmospheric turbulence alters the peak irradiance of an HEL (i.e., how tightly the HEL beam can be focused on a target). The diffraction limited focusing dependence, which varies as the inverse square of the wavelength (λ^{-2}), favors the use of shorter wavelengths. Beam spread due to turbulence alters the λ^{-2} dependence of the peak irradiance and becomes the dominant factor for shorter wavelengths as C_N^2 increases. For this case the peak irradiance wavelength dependence becomes $\lambda^{2/5}$ [3].

Measurements of atmospheric turbulence have been performed at WSMR which shed light on what time of day and year an HEL can best be tested [13]. Figure 1 shows a daily plot of turbulence for two of five elevation sensors - one at 5 and the other at 32 m above the ground. Turbulence tends to increase toward midday and decrease at higher elevations. In fact, during the summer turbulence becomes a very serious problem in the 3-5μm window as will be discussed in a later example.

CROSSWIND

The transverse-to-the-beam or crosswind has a significant effect on HEL beam propagation. When a crosswind is present, it tends to remove from the HEL path the heated atmosphere caused by absorbed beam energy which otherwise might result in thermal blooming of the beam. The stronger the crosswind the more efficiently the heated atmosphere is removed from the beam, thermal blooming being inversely related to crosswind speed. When a moving target is being fired at, the slewing of the HEL beam contributes an additional component of crosswind to the atmosphere along the HEL beam path which will of course vary with slewing rate and distance from the HEL source. The significant result of this is that even when there is a naturally occurring wind, slewing can result in zones along the HEL path where the slewing and natural crosswind components nearly cancel (i.e., stagnation zones are created) and greatly increase the effects of thermal blooming. Following the same line of thought, slewing can be used quite advantageously to reduce thermal blooming when there is little natural crosswind. What is important is that crosswind data is being amassed for HEL support. The effect of these results will be deferred to an example which will be discussed later.

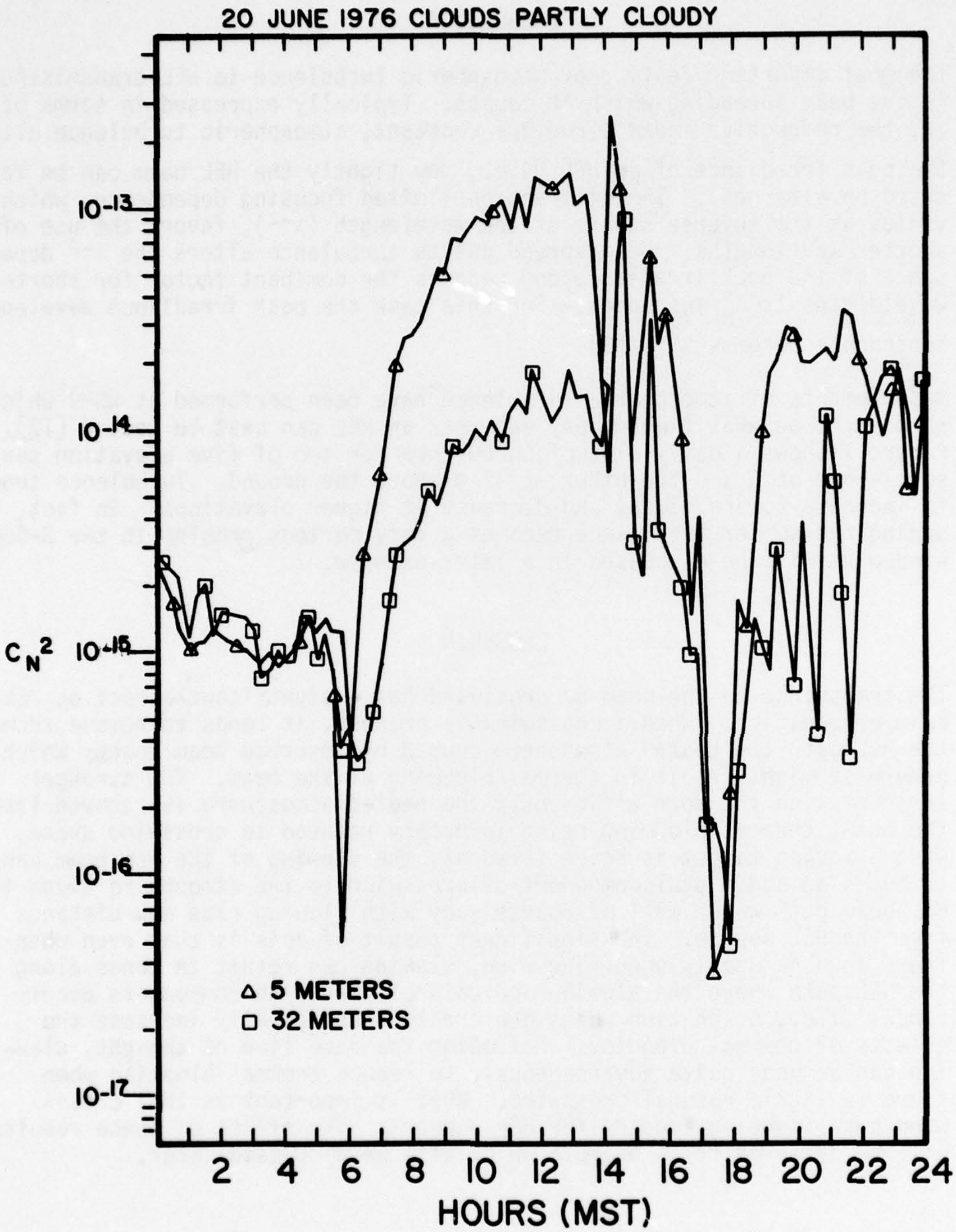

Figure 1. Hourly thermal turbulence. Measurements of C_N^2 at WSMR for elevations of 5 m (triangles) and 32 m (squares). (Data obtained from D. L. Walters, C. L. Norton, and G. B. Hoidale, ASL, WSMR.)

GASEOUS ABSORPTION

Gaseous absorption is highly frequency dependent, which complicates HEL source transmission predictions, and chemical lasers compound this problem by their multiline outputs. Gaseous absorption is generally characterized by two types of absorption mechanisms - line and continuum absorption. The expected transmission for the individual laser lines for the four sources discussed here are given in a recent review article by Kelley et al. [16], which also gives details about the individual absorbers such as concentration variability and effects of altitude. Line absorption is in general more sensitive to laser frequency and pressure broadening, whereas the water vapor continuum absorption is quite temperature dependent.

By far the most important atmospheric gaseous absorber is water vapor. Substantial water vapor continuum absorption is found in both the 3-5 and 8-12μm windows, and in addition there is strong water (H_2O) line absorption plus singly deuterated water (HDO) line absorption at DF wavelengths. A recent review article by Roberts et al. [17] indicates a very strong temperature dependence of the water vapor continuum in the 8-12μm region and details water vapor absorption problem areas which have not as yet been resolved in the 3-5 and 8-12μm regions.

The ASL has already made significant contributions to answering the question of the magnitude of the water vapor continuum in the 3-5μm window region using a DF laser source [18]. Previously, the continuum values for modeling purposes were extrapolations of the Burch data taken at 65°C and higher [19]. The ASL has made both longpath absorption cell and spectrophone measurements [25] of water vapor absorption by using mid-latitude summer model conditions (i.e., 14.3 torr of water vapor buffered to 760 torr total pressure at 23°C). From these measurements the best values of H_2O line (very weak at DF wavelengths) and HDO line contributions are subtracted to obtain the residual so-called continuum. Both measurement systems yielded a continuum approximately twice that of the Burch extrapolation which increases the thermal blooming by about 30 percent. To further check the magnitude of the continuum results, HDO line measurements were performed [20] which agree well with the most recent line parameter compilation predictions of the Air Force Geophysics Laboratory (AFGL), and an HDO depleted water sample* with one-fiftieth the normal concentration of HDO was used [18]. It should be pointed out that the HDO concentration does vary geographically [21]. The HDO depleted water measurements which contain no line absorption and agree with the continuum derived from the total water vapor absorption measurements are compared with the Burch extrapolation in Figure 2. Measurements are presently under way to obtain temperature and pressure dependencies at DF and HF (using a line laser), and at CO (using a tunable diode laser) frequencies.

**The HDO depleted water sample was obtained from Science Applications, Inc., Ann Arbor, MI.*

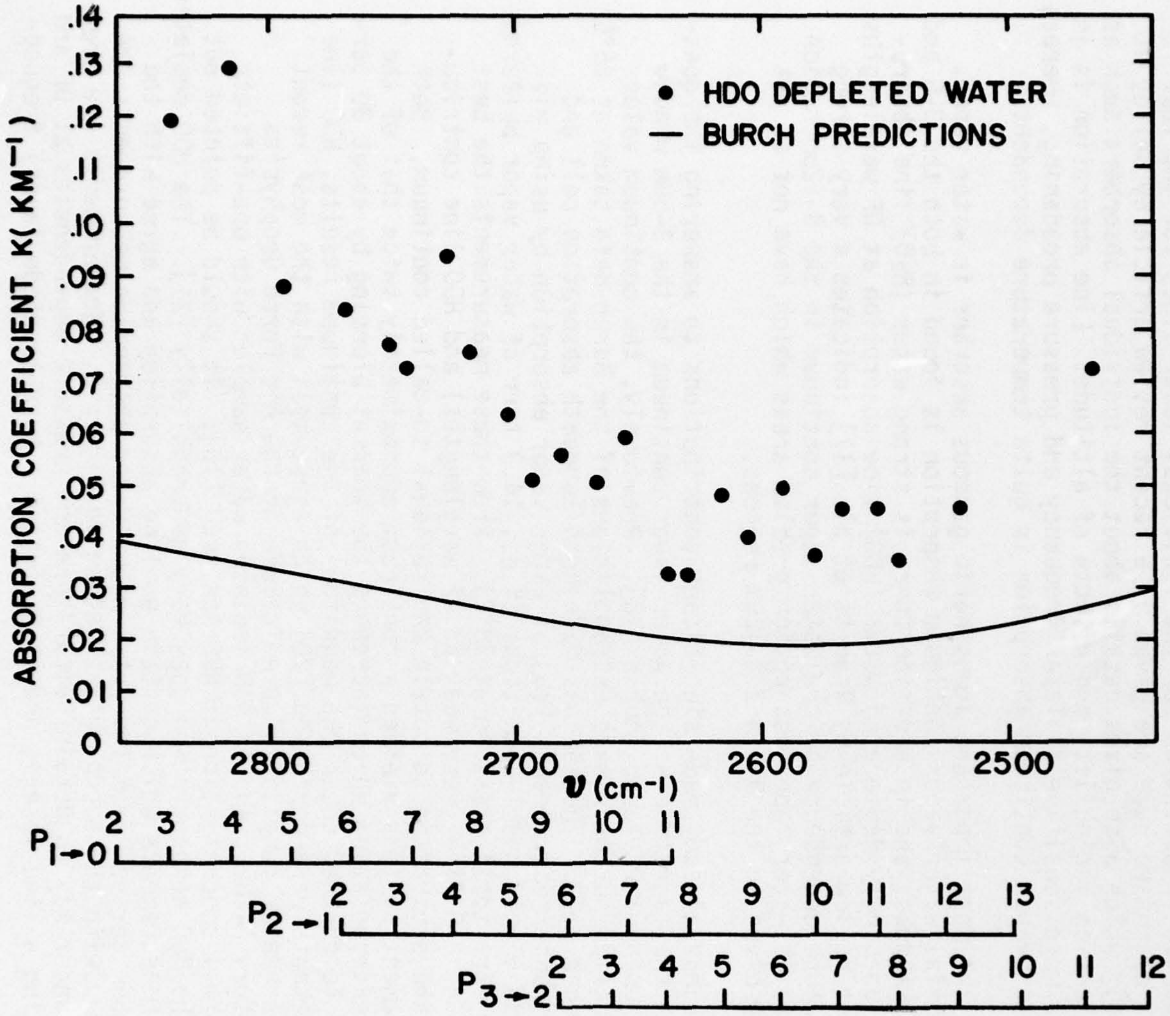

Figure 2. Water continuum. Measurements of water continuum for 24 DF laser lines in the 3.0-4.0μm spectral region using an HDO depleted water sample.

After the question of water vapor absorption has been resolved, battlefield related gaseous absorption will be investigated. Some measurements have already been made on DF absorption by propane and butane [22]. The Air Force Weapons Laboratory (AFWL) has been developing CO_2 lasers which radiate between 9 and 10μm. For high altitude operation CO_2 and ozone (O_3) are major absorbers. The ASL has measured the scaling parameters required to predict high altitude (low pressure and temperature) O_3 absorption coefficients [23] and assisted in CO_2 kinetic cooling related experiments with the AFWL.* Questions of this nature often arise and are addressed on a priority basis.

AEROSOL ABSORPTION AND SCATTERING

In gaseous absorption there are many discontinuities due to narrow line absorptions, whereas in the case of aerosol absorption and scattering the frequency dependence is a smoothly varying function; yet, the total aerosol extinction can vary orders of magnitude for different meteorological conditions. Scattering for the most part causes minimal problems except under very low visibility conditions such as dust storms, fog, rain, or snow. Even in this case, the scattering effect is not as severe as aerosol absorption since it is the absorption of energy which heats the atmosphere and induces thermal blooming. In general, the ASL's research measurements have been in the field of dry aerosols or particulates. Wet aerosols are now being addressed though with such new devices as the calibrated aerosol spectrometers [9] and in situ spectrophones [10]. Recent measurements of fog and haze in West Germany (Grafenwöhr) have resulted in very interesting vertical inhomogeneity profiles of the aerosol size distribution [14]. These data show that the extinction coefficient can increase by one or two orders of magnitude in the first few hundred meters above ground. This means that slant path transmission through such an atmosphere may be much less than along a corresponding horizontal path near the ground.

Particulate absorption has been under investigation for some time at the ASL. Particulate absorption can vary from a small effect under clear conditions to absorption comparable to or greater than the total gaseous absorption under turbid conditions. Characterization of atmospheric particulates requires both size distribution and composition because of differences in the imaginary refractive indices of various substances. For example, particulates less than about 2μm in diameter are primarily ammonium sulfate and carbon, whereas 2-50μm particulates are primarily silicate clays, carbonates, and quartz. As in the case of wet aerosols where the total liquid water content relates fairly well to total absorption, the total mass of particulates gives a reasonable estimate of the total absorption. This generalization should not be carried too far, however, since particulate absorption varies geographically because of composition, is wavelength dependent, and little is known of its variation with elevation. For example, a factor of 2 or 3 difference in absorption is often encountered between 10.6 and 9.2μm.

**Measurements of the effects of water vapor on CO_2 kinetic cooling were performed at the ASL by B. Heimlich, AFWL, Albuquerque, NM.*

Descriptive models of the atmospheric dust at WSMR are being prepared based on measurements of mass loading in the atmosphere, particulate size distributions, compositional analysis, and imaginary refractive index measurements for different size ranges of particles found in the air. In addition, a program has been initiated to measure the imaginary refractive index and composition of atmospheric particulate samples from a wide variety of localities in North America, Panama, Europe, and the Mideast. The objective of this work is to determine the typical mean values and extremes of variability of the optical constants of these samples and to relate this information to geographical, seasonal, and meteorological information, to permit construction of realistic models of atmospheric particulates in localities of potential military interest. Some preliminary results of this work have recently been reported by Lindberg et al. [24]. Pellet spectrophones allow accurate direct measurement of particulate absorption instead of total extinction in the 3-5 and 8-12μm window regions [8]. Models for low visibility and battlefield environments are of the most importance, and directly related to them will be the analysis of countermeasure smokes which at present are more effective in the 3-5 than the 8-12μm window.

A WSMR EXAMPLE

A comparison will be made for DF and CO_2 continuous wave (cw) HEL sources with the same range and diameter of focusing optics. Average monthly data will be used for comparisons although it should be emphasized that daily and even hourly or shorter variations of the atmosphere can cause substantial changes in transmission. The atmospheric pressure at WSMR is typically about 655 torr with ±2% variations daily and throughout the year [25]. The average water vapor varies seasonally from around 3 torr during most of the winter to over 10 torr during the summer, with several torr variation from day to day. Average daily temperatures range from 7 to 27°C throughout the year with daily variations of 20 or more degrees. Finally, average monthly crosswinds for a typical site vary from 2.1 to 5.6 m/sec with several meter per second variations during the day, the strongest winds occurring in the late afternoon. These results are summarized with the corresponding gaseous absorption coefficients of a DF laser (Navy ARPA Chemical Laser, NACL) [26] and a 10.6μm P(20) CO_2 laser in Table 2.

Neglecting for the moment the effects of aerosol extinction and turbulence, the average relative critical powers (i.e., the laser power which gives the maximum power on target) for the cw DF and CO_2 lasers using the data in Table 1 and an optical path where the absorption coefficient times the pathlength is much less than one are shown as a function of month in Figure 3.

The corresponding relative peak irradiance on target is shown in Figure 4.

TABLE 2*

PARAMETERS REQUIRED TO CALCULATE THE CRITICAL POWER OF A cw DF AND cw CO_2 LASER

Month	Average Crosswind Speed (m/sec)*	Average Water Vapor Pressure (torr) (Hoidale, 1974)	DF Gaseous Absorption Coefficient (km^{-1}) (White, 1976b)	CO_2 Gaseous Absorption Coefficient (km^{-1})**
J	2.2	3.0	0.038	0.10
F	2.8	2.9	0.038	0.10
M	4.2	3.0	0.038	0.10
A	5.6	3.1	0.039	0.10
M	4.8	4.1	0.040	0.11
J	3.9	6.1	0.051	0.13
J	2.4	10.4	0.074	0.20
A	2.2	10.5	0.074	0.20
S	2.4	8.3	0.063	0.16
O	2.6	5.4	0.055	0.12
N	2.2	3.8	0.044	0.10
D	2.1	3.2	0.040	0.10

**Source:* *crosswind data of D. L. Walters and C. L. Norton, WSMR, NM.*

***Calculations presented here were performed by Science Applications, Inc., Ann Arbor, MI, using the most recent update of the line parameter compilation (McClatchey et al., 1973).*

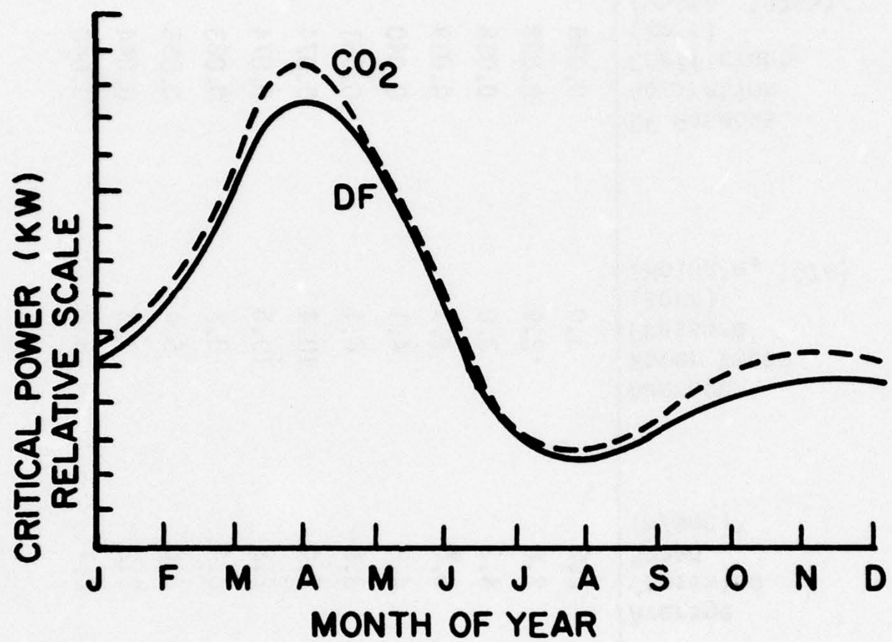

Figure 3. Critical power. Using the data in Table 2, this represents the maximum relative power for achieving the peak irradiance on a target for a cw DF and cw CO_2 laser.

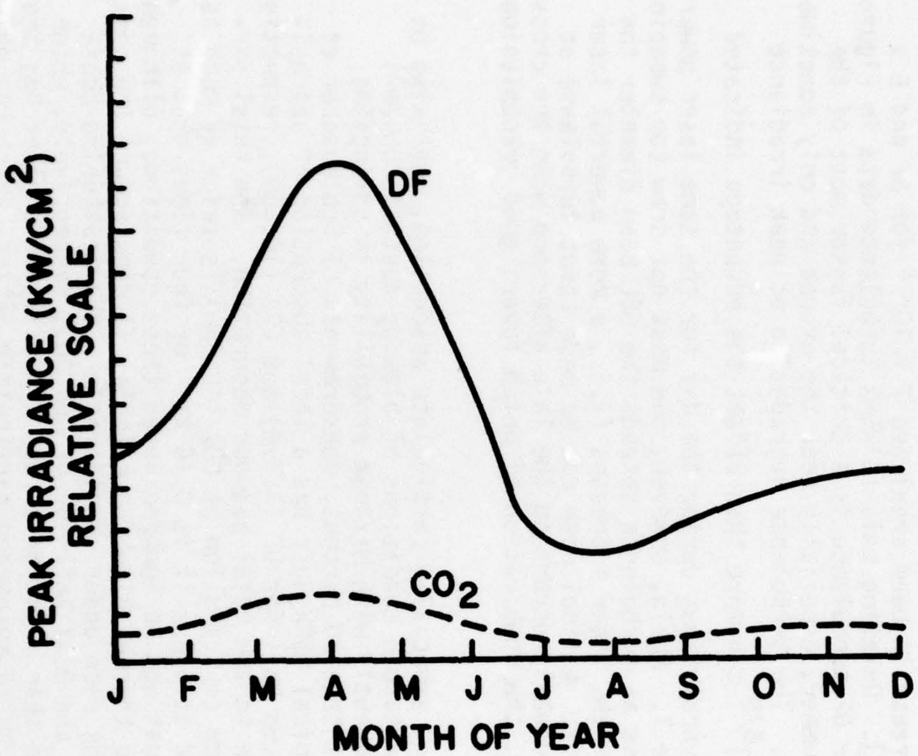

Figure 4. Average peak irradiance. The average relative irradiance corresponding to the critical powers of Figure 3 where the laser spot is defined as twice the airy disc area for a cw DF and cw CO_2 laser.

The critical power is directly proportional to wavelength and inversely proportional to absorption coefficient. The nearly equal critical powers for cw DF and CO_2 are due to coincidental cancellation of these two non-related effects. The nearly order of magnitude larger relative peak irradiance in Figure 4 for DF over CO_2 is due to the λ^{-2} diffraction limited focusing dependence. It should not be taken from this, however, that DF is much better than CO_2.

Turbulence causes more beam spreading of DF radiation than CO_2. The levels at which the turbulence C_N^2 term becomes critical (i.e., causes a factor of 2 increase in beam area) are 7×10^{-15} for DF and 6×10^{-14} for CO_2 [13]. Relating this to WSMR turbulence data in Figure 1 reveals that for DF turbulence is a critical factor most of the time during the summer, especially near the ground and only sometimes for CO_2 at midday. The turbulence degradation of peak irradiance which goes as $(C_N^2)^{6/5}$ can more than offset the advantage indicated in Figure 4 at several times during the day for the same laser power as shown in Figure 1. Again, however, one must not draw too sweeping conclusions because as turbulence spreads the HEL beam diameter the critical power for the laser increases (i.e., a more powerful laser source can be used). A final note can be made about turbulence at WSMR. A minimum usually occurs in the late afternoon when the cross-wind is a maximum, the combination of which favors good transmission at that time.*

Aerosol extinction, especially particulate absorption, must also be considered. Under turbid conditions of blowing dust ($1000 \mu g/m^3$) which occur infrequently with maximum probability in springtime afternoons of less than 10 percent, measurements of Schleusener et al. [27] imply typical WSMR dust has a total absorption of approximately 0.04 and 0.08 km^{-1} for DF (3.8μm) and CO_2 (10.6μm), respectively. This is comparable to the total gaseous absorption. The total particulate absorption contribution at CO_2 (10.6μm) is twice as much as at DF (3.8μm), and at 9.2μm it is 0.16 km^{-1} or four times that at DF. Scattering must not be ignored under these conditions; although it does not add to thermal blooming effects, it does reduce the peak irradiance. In the case under consideration, the scattering coefficients are 0.35 and 0.11 km^{-1} for DF and CO_2, respectively, which favors CO_2 by more than a factor of 3. Typically on a clear day there is from 5 to $50 \mu g/m^3$ of suspended particulate matter, which has only a minor effect on transmission.

**Source: crosswind data of D. L. Walters and C. L. Norton, WSMR, NM.*

CONCLUSION

This report has examined the measurements required for transmission predictions to support successful testing of an HEL system at WSMR. The reason for detailed measurements of turbulence, crosswind, gaseous absorption, and aerosol extinction is that each can cause serious HEL beam degradation by its presence or absence as in the case of crosswind. The ASL does have the measurement capability and is rapidly completing the necessary data base to adequately support HEL field testing at WSMR. Unless a test facility has sufficient measurement capabilities to handle turbulence, crosswind, gaseous absorption, and aerosol extinction plus their temperature, pressure, and humidity dependencies, field testing can be quite wasteful. If predictive models are lacking in any vital area, anomalous effects (whether they are recognized or not) can be misinterpreted and incorrect conclusions derived.

There are still many questions which remain unanswered in terms of atmospheric transmission. The physical mechanism of water continuum absorption is not understood, nor are accurate pressure and temperature scaling factors available in the 3-5 and 8-12μm atmospheric windows. Absorption by wet aerosols and advantages and disadvantages of pulsed versus cw operation must be investigated. Use of HEL's in high altitude environments pose many new problems such as kinetic cooling by CO_2 and open the way for the use of HF and CO lasers which are severely attenuated by water vapor at lower elevations. Also there is the question of the effects of battlefield environment and countermeasure smokes which have not as yet been characterized. Further studies of geographical variations of the important atmospheric parameters need to be done. The ASL has been able to answer many difficult problems already in the area of atmospheric transmission and more importantly has developed much of the measurement capabilities required to answer those remaining.

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